

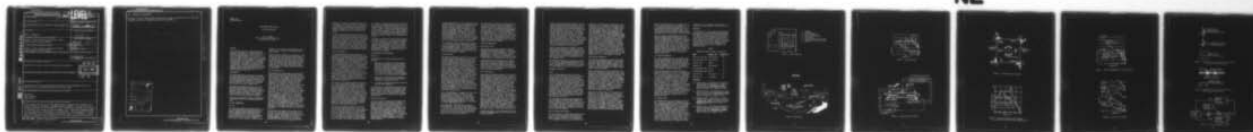
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A SUB-SEISMIC TEST PLATFORM AS A MOTION EXCITER.(U)  
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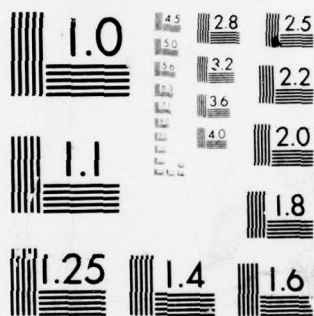


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20. Abstract (continued)

pneumatic control system which maintains the test platform level to 0.001 arc seconds and free of vibrations greater than  $10^{-8}$ g.

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## A SUB-SEISMIC TEST PLATFORM

### AS A MOTION EXCITER

Bill J. Simmons  
Frank J. Seiler Research Laboratory  
USAF Academy, Colorado

#### ABSTRACT

The technique and use of a large pneumatically supported test platform as a motion exciter is described. Maximum motion capability, and the effects of system resonances of the 450,000 lb., servo controlled, isolation test platform is shown for use in tests of motion sensors (e.g., inertial navigation gyros and accelerometers, seismometers, and tiltmeters). The possibility of large test specimens, such as a complete navigation system, is considered. Information is provided on the construction of the test platform and the electro-pneumatic control system which maintains the test platform level to 0.001 arc seconds and free of vibrations greater than  $10^{-8}g$ .

#### INTRODUCTION

This paper describes the design and performance of an isolated test platform (Iso-pad), at the USAF Academy's Guidance and Control Laboratory, in use on testing and research programs of inertial navigation components and system, and in particular describes the use of the Iso-pad as a precision motion exciter for sensor response tests.

The Guidance and Control Laboratory is jointly operated by the Department of Astronautics and Computer Science, and the navigation division of the Frank J. Seiler Research Laboratory (FJSRL) an AFSC lab based at the Academy. The laboratory provides a facility for testing and research in state-of-the-art inertial guidance equipment.

Objectives of the present effort were measurement of the motion limits of the Iso-pad excitation modes.

#### PHYSICAL CONSTRUCTION

##### Facility

The Iso-pad is located on the ground floor of the six floor building which houses the Academy's academic program including classrooms, laboratories, and faculty offices (Fairchild Hall). There are parking lots, light vehicle traffic, building heating, and air conditioning equipment within 100 ft. of the Iso-pad. Although the entire area is remote from heavy industry distur-

bances, it is clear that a considerable amount of motion noise is created in the proximity of the test facility.

Figure 1 shows the layout of the laboratory. Note the nine test piers which are an integral part of the Iso-pad; the bulk of the Iso-pad is housed in a room below the inner laboratory. The test piers protrude through holes in the laboratory's false floor. The "sealed" inner laboratory, designed as a Class 10,000 clean room, covers about 2,200 square feet of floor space; this sealed Iso-pad area has separate air conditioning ( $67^{\circ} \pm 1^{\circ}F$ ) and air lock entry.

##### Iso-pad Construction

The Iso-pad at the USAF Academy is constructed of steel reinforced concrete. The pictorial sketch, Figure 2, shows main equipment items and construction features of the Iso-pad. The Iso-pad is located in a sub-floor room beneath the inner laboratory, with nine integral test piers protruding upward through the "false" floor of the inner laboratory. It appears as a twenty-five foot square from the top with nine circular piers rising 2.5 ft. up from the main block of the Iso-pad. These piers are tied to the main block with reinforcing bars and were poured monolithically with the block. The bottom of the block has a cruciform shape that is 4.5 ft. high; this allows for location of the means of Iso-pad "lift." The total platform weight of 450,000 lbs. is supported by twenty undamped pneumatic isolators, "actuators", and floated approximately 1/2 inch above the base slab. The peculiar shape of the block was designed to cause its center of gravity to be located near the level of the supporting pistons so as to minimize the coupling between the various modes of vibration. In addition to the shape, hollow sonotubes buried in the upper slab portion of the block contribute to the proper location of the center of gravity(1).

The base slab which supports the pneumatic isolators is 24 in. reinforced concrete on grade of 4,000 psi compressive strength. The slab, or seismic mass, which is physically distinct from the concrete basement floor around it, rests on a compacted aggregate fill three ft. in thickness. This three ft. base course is separated from the

subgrade by a continuous polyethylene vapor barrier layed over a two inch concrete base placed on the subgrade. The subgrade itself is a native granular cohesionless decomposed granite material (natural formation, not fill). Professor Ken Tsutsumi of Tufts University specified the base design.

The isolation/control system on the original installation was designed and installed by the Barry Controls Division of the Barry-Wright Corporation. This system consisted of control of air into three banks of the 20 isolators, the flow to each bank determined by demand of a corresponding height-sensor/flow-regulator valve. This "passive" system, still used as a back-up configuration, maintained the Iso-pad, in a floated mode, parallel to the base slab beneath it. The average operating pressure of the 20 pneumatic isolators is 80 psig.

#### Passive Performance

A soft-sprung passive isolation system does an excellent job of eliminating ground motion of the base slab at frequencies well above the suspension natural frequency. The amplitude attenuation behaves essentially as a second order low-pass filter. Transmissibility at low frequency is 1. The price that must be paid for achieving this isolation from base motion, however, is a high susceptibility to disturbance forces on the platform itself. The transmissibility of force disturbances at low frequency is equal to  $1/K$ , where  $K$  is the stiffness of the supporting springs. Since  $\omega_n = [K/M]^{1/2}$ , lowering the platform natural frequency increases the platform sensitivity to force disturbances by  $1/\omega_n^2$ . The desired natural frequency of the passive isolation system then amounts to a trade-off between the amount of isolation against base motion versus force disturbances that is desired<sup>(2)</sup>.

The choice of a soft-sprung supporting structure or a rigid ground coupling depends to a great extent on the application. For many experiments, where high frequency accelerations can excite natural frequencies in the test device, the low-natural-frequency, passive system is to be preferred. In this case, the low frequency motions of the platform are of little importance since they do not impart any appreciable acceleration to the item under evaluation. In the case of inertial component testing, however, these small-amplitude, low-frequency motions are intolerable. In gyro testing, the tilt orientation angles and angular rates are of greatest importance, while the tilt angles and linear accelerations are of greatest importance in accelerometer testing.

The Iso-pad has a spring stiffness  $K = 580,000$  lbs./ft. and a natural frequency of 1 Hz. For this system, a motion sensitivity of approximately 20 micro-inches/lb. results. If, during testing operations, no personnel activity occurs on or around the isolation platform on which the test table is mounted, the largest disturbance forces to the platform will be caused by low frequency base slab motion and atmospheric pressure changes within the room. The latter disturbance results

in a change in buoyance force exerted on the platform. Typically, peak deflections from level would be about 0.1 arc seconds at short periods on a low frequency (mostly 24 hour period) base slab motion of 2 arc seconds. There is a significant reduction in vibration levels above 3-5 Hz. This is shown in Figure 3 which compares the power spectral density (PSD) of a vertical sensor on the seismic mass to the PSD of a vertical sensor on the floated passive Iso-pad.

In general, maintenance of such "quiescent" personnel activity within a test laboratory is impractical. More importantly, even such motion levels as 1 micro g low frequency and 0.1 micro g at high frequency are unacceptable in terms of test base stability requirements for tests of the present inertial grade instruments. Therefore, the Iso-pad was modified to an active control system as described in the following:

#### ACTIVE-CONTROL ISO-PAD FEATURES

##### Objectives

The objectives of the active stabilization are threefold:

1. Suppression of six-degree-of-freedom angular and linear movements of the block under the influence of disturbance torques and forces. These disturbances are typically caused by floor/wall vibrations; standing air waves in the inner laboratory room; other pressure variations; due to doors, air conditioning, etc.; coupled base motion; and limited personnel activity (e.g., adjusting test equipment).
2. Provisions for a seismic motion simulation capability by applying known error signals as a reference into the control loops.
3. To relate the Iso-pad orientation to inertial, not base floor, references.

For suppression of disturbance induced motion, the great inertia of the block itself provides a high degree of passive isolation for frequencies above 20 Hz. Based on this, and the anticipated test requirements, the active stabilization and control system is designed to be effective up to approximately 20 Hz.

##### Servo Control Devices

In order to remove the effects on base motion and force disturbances on the platform, a means of applying a controlled force to the platform is required. This has been accomplished with two separate systems. First, the air pressure in the supporting pneumatic actuators is varied in order to remove the low frequency transients (below 0.1 Hz). The low frequency angular motion about the horizontal axes is measured by Hughes TM-3 tilt-meter (0.001 arc sec resolution). At low frequency the other four degrees-of-freedom, x, y, and z translation and azimuth, continue to be "floor-based" references until development of suitable inertial sensors.



Secondly, motion above 0.1 Hz is sensed inertially by Geotech SL210/220 long period seismometers; and the motion in all six-degrees-of-freedom is obtained. The three translation motions are obtained as an average of two horizontal or four vertical seismometer signals. The three angular motions are obtained as differences of pairs of matched seismometers. The angular resolution is inversely proportional to the separation of the two seismometers; as a result, the resolution of a difference signal from the two SL210's at opposite sides of the pad, (i.e., a 25 ft. "leg") is better than the best available angular accelerometer.

The six-degrees of high frequency motion signals,  $f > 0.1$  Hz, are amplified, conditioned, and applied as correction forces to the Iso-pad by means of electromagnetic shakers. The eight shakers in use, four vertical and four horizontal, are Ling model 411 units capable of about 13 pounds thrust in the non-forced-air cooling mode.

#### System Operation

The twenty air tanks are connected so the pressure of outside pairs (eight total) may be varied to tiltmeter command. The remaining "inside" tanks are inner-connected and are pressure controlled within a narrow pressure range to maintain the Iso-pad height to within a few micro-inches. The outside, "tilt", tanks are controlled in pairs over a wider range,  $72 \pm 7$  psig, to correct tilt errors. Figure 4 depicts, for one angular and one linear degrees-of-freedom, the main components used in the vertical system. At null conditions, the pneumatic actuators apply the correct lift to maintain the Iso-pad at 0.5 inch above the seismic mass in a level condition. If a height error develops, air is input or exhausted, to the 12 inside tanks until the null is restored. If a tilt error develops the amplified TM-3 signal is applied through electric-to-pneumatic transducer, partial supported resistor, and flow booster, to the pairs of "outside" tanks to input air into the low side and exhaust air from the high side. This push/pull arrangement is used in order to apply rotational correction with a minimum effect on the linear height control loop.

Sum ( $\Sigma$ ) and difference ( $\Delta$ ) signals are formed from the seismometer outputs, and applied to the shakers as shown in Figure 4. The sum signal corresponds to a vertical motion, and difference signal corresponds to an angular motion of the Iso-pad in the frequency range  $0.1 < f < 20$  Hz. The shakers apply appropriate forces to counteract the sensed high frequency motion.

This description illustrates the principles of system operation. One could picture Figure 4 as an E-W angular or a N-S angular servo illustration. In practice, the vertical servo loop uses the sum, not or just two, but of all four vertical seismometers, and the vertical correction forces are applied by all four vertical shakers.

The high frequency servos for horizontal forces operates in a manner similar to the vertical controls described above. The three-degrees-of-freedom, N-S and E-W translation and azimuth rotation, are sensed by four horizontal seismometers and controlled by four horizontal shakers within a frequency range  $0.1 < f < 20$  Hz (see Figure 5). The shakers are based on four columns adjacent to the Iso-pad, and forces are applied to the Iso-pad in the c.g. plane. Low frequency actuators and sensors have been considered but none are in use pending availability of practical DC-0.1 Hz horizontal, inertial motion sensors.

#### STABILITY PERFORMANCE

##### Measurement Status

The Iso-pad active-control system is currently undergoing an improvement program to incorporate long period SL210/SL220 seismometers. The following data is as a result of previous and current system status. Currently, the Geospace HS-10 seismometers are those in use; and results, using a feature termed "tilt augmentation", are shown<sup>(3)</sup>.

Tilt augmentation is a feature in which an additional loop is provided by summing the tiltmeter output into the shaker actuators. This input, with proper compensation, improves performance of the HS-10 loops in the 0.002 to 0.15 Hz frequency band. The value of tilt augmentation to the SL210 loops has not been determined.

##### Active Performance

The closed loop frequency response of the high frequency angular control loop is shown in Figure 6. One can see that the system gives good attenuation at all frequencies except for around 0.02 Hz. At this frequency, neither of the two control loops is effective, because of insufficient control band overlapping. By augmenting the above-described angular control system with an additional loop, tilt augmentation, one can solve the bandwidth overlapping problems. The additional loop is provided by summing the tiltmeter output into the shaker actuators via a compensator. This compensator provides the proper high frequency roll-off to obtain a control bandwidth up to 0.15 Hz with a phase margin of about 50 degrees. The augmentation loop is then effective from about 0.002 to about 0.15 Hz. This fills in the gap so that closed loop control is provided between 0 and 20 Hz. Figure 7 shows the overall closed loop response of the complete angular control system for the horizontal axes of the isolation block as a power spectra density (PSD) comparison. The angular motion sensitivity to disturbance torques is attenuated by more than 20 db over the DC-10 Hz control bandwidth when referred to the passive isolation block.

Figure 8 shows PSD's of all six channels where the N-S and E-W angular servos are "ON", as well as the channel indicated<sup>(4)</sup>.

Figures 9 and 10 show some performance results obtained by the described control system. The N-S axis angular control system has been taken as an example. Figure 9 shows the angular response of the isolation block to 60 lb-ft step torque input. This was obtained by lifting a 5 lb. lead mass from one end of the seismic block. The angular signals shown were taken from the output of the tiltmeter under the three conditions: passive Iso-pad; low frequency tilt loop ON; and both low and high frequency angular loops ON. These responses were measured with the horizontal control loops inactivated to show the cross coupling of linear motion into the tiltmeter. The cross coupling appears in Figure 9 as a ripple at 2 Hz which is the natural frequency of N-S translation.

Figure 10 shows the angular response to ambient disturbances including a man walking on the false floor around the block and a door slamming in an adjacent room. The measurement bandwidth is from 0.2 Hz to 60 Hz. One can see that the high frequency control loop reduces the angular motion from about 0.01 arc sec to below 0.001 arc sec in that frequency band.

The PSD plots of Figure 8 do not extend to "near D.C."; however, previous measurements show that the 1-2 arc secs peak to peak daily level of the passive Iso-pad ( $10^{-5}$  Hz) are reduced to the milli-arc second range with the tilt servo controls.

#### CONTROLLED EXCITATION

##### Method

One of the most important uses of an active-control Iso-pad has been for imposition of known excitations to test specimens. For example, during a gyro test, a given frequency of angular vibration could be imposed about an E-W axis and the effect measured on the gyro performance. All motion in six-degrees-of-freedom at one test site could be measured, taped, and the playback used as excitation to the six channels of Iso-pad active control servos. The technique (Figure 11) is straightforward, and has been used in instrument comparisons. Excitation signals, from function generator, random noise generators (RNG), or tape are imposed on the tilt servo for low frequency excitation and the seismometer/shaker servo for high frequency excitation.

Two other forms of excitation used occasionally, are step-inputs to vertical shaker channels by means of weight lifts on the pad, and the use of a "floating" shaker, positioned on the Iso-pad without coupling to ground, but loaded with a 2 to 3 pound weight. The latter technique is sufficient to excite resonant modes of vibration in the Iso-pad and some test equipment.

##### Small Excitation Test Example

Use of the Iso-pad in the excitation mode has thus far been limited to extremely small motions as appropriate for comparison of precision instruments. The data in Figure 12 is a comparison of five instruments with milliarc second resolution

capability. Here, with the Iso-pad active; a sine wave excitation is imposed in the pneumatic (low frequency) controls to effect a N-S angular motion of 0.005 arc seconds at 0.15 Hz. It may be seen from the example, that the Iso-pad provides adequate background stability for making such low level measurements. The original purpose of the test, to prove milliarc second resolutions of these sensors was accomplished. The "absolute" magnitude of the excitation is an extrapolation of the scale factor, angle/volts of excitation, measured at a larger excitation by the appropriate calibrated angular sensor. The large excitation is then reduced to the desired level by means of a voltage divider; the assumption is made that the Iso-pad scale factor of response to excitation signal remains constant as the level of excitation is reduced by means of the divider. This technique was tested and the scale factor remained constant for angles of the order of 1 to 20 arc seconds. In this example, the use of a calibrated TM-3 tiltmeter was appropriate to the 0.15 Hz angular excitation.

##### High Frequency Capability

The limits on pad motion as a high frequency exciter are set by the shaker capacity. As it stands now, these capacities are limited to about 113 lb. rms force. These values could be doubled if air cooling is supplied the model 411 shakers; and of course, if a project warranted the expense, larger shakers could be installed.

There are resonances in the Iso-pad which are outside of the servo control range of DC-20 Hz. Tests performed to determine Iso-pad maximum capabilities revealed that these resonances were excited by subharmonics within the control range. For example, the 65 and 67 Hz resonances due to Iso-pad bending are excited by 13 and 13.4 Hz, the fifth subharmonic angular excitation respectively. This effect was measured in the servo-off, or passive mode, since modification work was in progress. One would expect this to be greatly reduced when servos are activated. The subharmonic excitation effect is generally not expected to be a significant test limitation for most test specimens.

Figure 13 shows pad motion to 100 Hz, where the excitation is, as shown, shaped to a random noise output from 3 to 45 Hz and applied as an angular E-W motion. The output is measured by a calibrated S-500 vertical accelerometer on the East pier. Note that a difference in two accelerometers, roughly twice the output of one, gives the angular acceleration. The output is plotted as a square root of the accelerometer output power spectra so that the data is "voltage"; proportional to angular acceleration, information. The significant anomalies, the anti-resonance at 44 Hz and resonance at 67 Hz, are well out of the specified control range.



Figure 14 shows pad motion to an excitation of 4 to 45 Hz vertical motion from two shakers only (N & S shakers were temporarily unavailable). A single S-500 vertical accelerometer on the center pier provides the vertical motion output. The curve shows any effect on higher frequency natural resonances in the vertical mode, e.g., the 58.3 Hz.

These two plots are representative of the six-degree-of-freedom excitation modes which can be imposed by shaker motion. The absolute value of motion, at maximum shaker excitation, is indicated on the vertical motion plot (Figure 14). With an excitation 3-amp rms, 4 Hz, to E-W shakers for vertical motion, the output of the vertical S-500 "accelerometer" shows a value of 92 micro g rms. Maximum output motion at other frequencies may be obtained from the accelerometer plot in Figure 14. (Actually, the vertical motion with all four shakers activated would be twice the values obtained in this test).

#### Low Frequency Capability

The limits on pad motion as a low frequency (LF) exciter are determined by the rate that the pneumatic actuator pressure can be changed. The air booster, Moore part 61H, provides a significant increase in rate of air flow from the electric-to-pneumatic transducers; but due to the large actuator volume, motion above 1 Hz, as a result of LF excitation, is rather insignificant.

Figure 15 shows angular pad motion measured by Hughes TM-3 Tiltmeter, as result of a random noise input to the E-W tilt loop. The 1.1 Hz resonance is the Iso-pad E-W angular resonance. The absolute value of the magnitude of the maximum motion is shown at two frequency points: At 3 Hz, the maximum tilt excitation is 85 micro radians/sec<sup>2</sup> p-p; while at 0.27 Hz, the maximum is up to 64 micro radians/sec<sup>2</sup> p-p. It may be seen from Figure 16 that the motion capability is increasing rapidly (approximately 20 db/decade) with decreasing frequency. At near DC the tilt angle is a more meaningful limit. The diaphragm positions of the pneumatic isolators are capable of about 1/4 in. variations. Safety devices prevent extensions of greater amplitude; this places a limit on the maximum tilt at about 5.7 arc minutes p-p, the maximum tilt at DC.

#### Load Weight Limits

The maximum weight of a test specimen on the Iso-pad, (i.e., D.C. capability) is dependent on the test location and whether changes to the pneumatic actuator set-up are warranted. For a test pier location at a cardinal point, the present weight limit is about 5,000 lbs. A pair of pneumatic actuators would operate at about 90 psig vs. the nominal 80 psig. And, considering the small change in Iso-pad inertia that a 5,000 lb. load would effect, the motion characterization would be relatively unaffected. There are possibilities of accommodating a larger load than 5,000 lb. For example, it is possible to use the center pier for a test so that the load is shared by all actuators; it may be practical to increase the supply

pressure; and it is possible to rearrange the actuators to better support a side or corner load.

#### CONCLUSION

The objectives were met of obtaining Iso-pad motion excitation limits for high-frequency (HF) angular and translation modes, and the low-frequency (LF) tilt modes. As discussed above, there are presently no provisions for LF translation and azimuth modes, and it was not possible to obtain LF vertical excitation motion due to temporary inactivation of that control loop. Typical frequency response plots have been covered in the foregoing (see Figures 12-16); Table I shows a summary of the excitation limits.

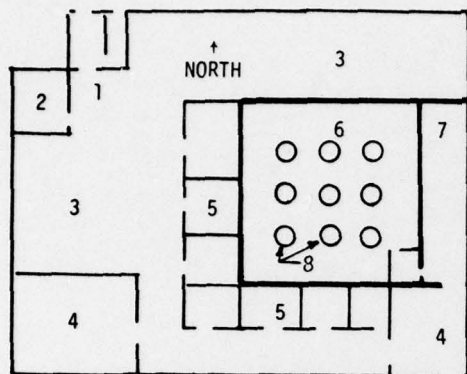
TABLE I

Maximum Excitation at Typical Frequencies

MODE	MOTION x 10 <sup>6</sup>	FREQUENCY HZ
N-S "Tilt" Axis (HF)	1350 rad/sec <sup>2</sup>	16
E-W "Tilt" Axis (HF)	1380 rad/sec <sup>2</sup>	16
Vertical (HF)	3800 g	16
Azimuth (HF)	1640 rad/sec <sup>2</sup>	16
N-S Translation (HF)	2400 g	16
E-W Translation (HF)	2400 g	16
N-S Tilt (LF)	64 rad/sec <sup>2</sup>	0.27
E-W Tilt (LF)	64 rad/sec <sup>2</sup>	0.27

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- (2) Lorenzini, Dino A., "Active Control of a Pneumatic Isolation System," AIAA Paper No. 72-843. American Institute of Aeronautics and Astronautics, Stanford, CA., August 14, 1972.
- (3) Brodersen, Emil, "Stabilization of a Seismic Isolation Block, Inertial Instrument Testing," AIAA Paper No. 74-857. American Institute of Aeronautics and Astronautics, Anaheim, CA., August 5, 1974.
- (4) Simmons, Bill J., "Multi-Sensor Measurement of the Motion Stability of an Active Controlled Isolation Test Pad," AIAA Paper No. 75-1081. American Institute of Aeronautics and Astronautics, Boston, MA., August 20, 1975.



1. Entrance
2. Equipment Vault
3. Class Equipment Area
4. Technician Work Areas
5. Office Areas
6. Iso-pad "Sealed" Inner Lab Area
7. Computers & Test Controls Area
8. Test Piers

FIGURE 1. Layout of G&C Lab

## ISO-PAD

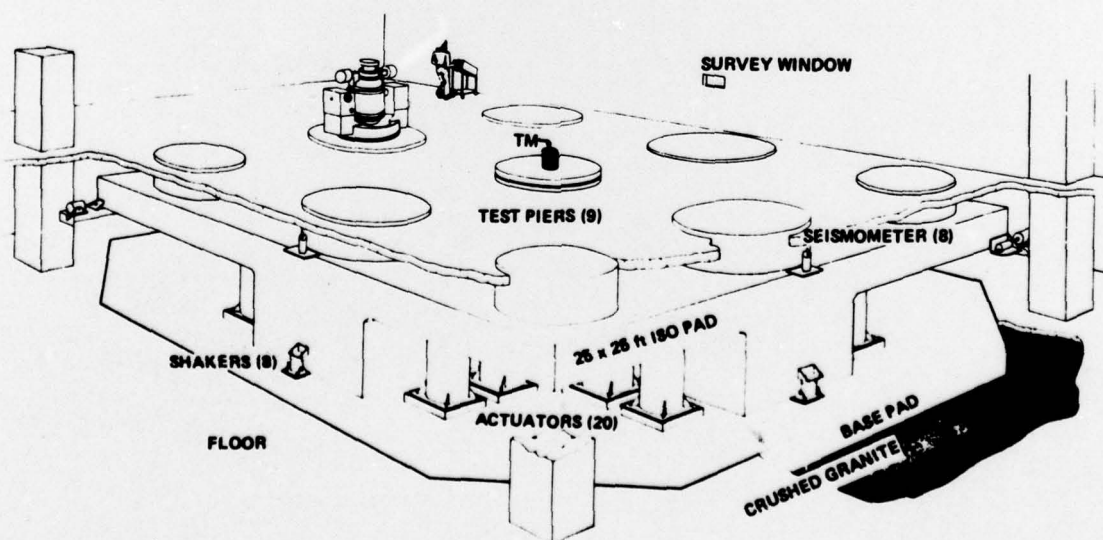


FIGURE 2. Iso-pad Pictorial

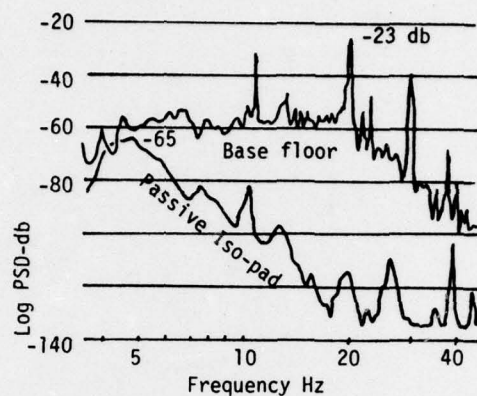


FIGURE 3. Passive Isolation

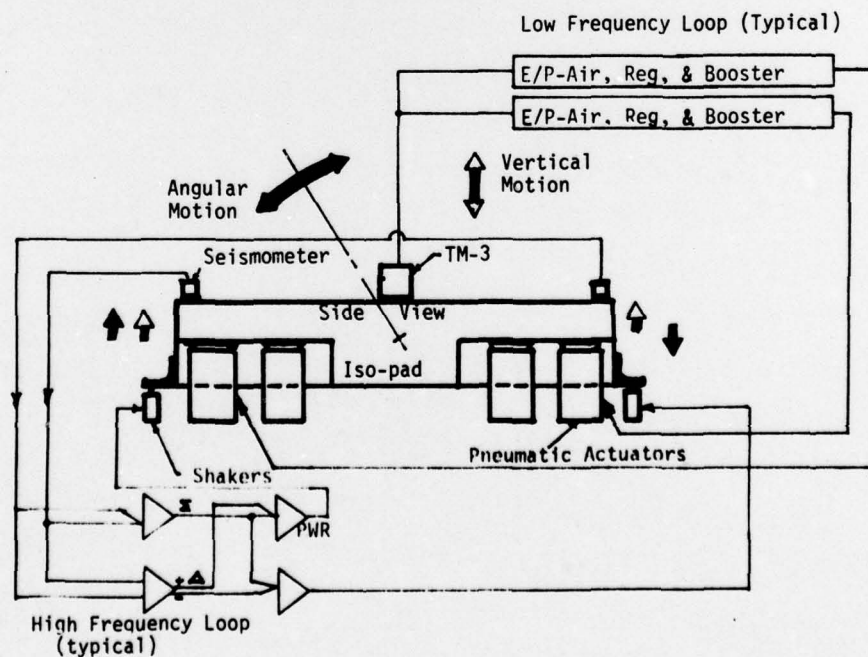


FIGURE 4. Iso-pad Vertical Excitation



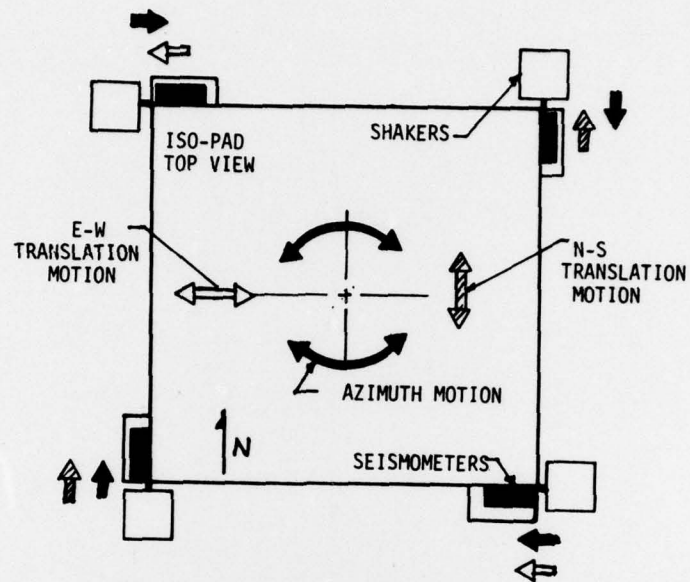


FIGURE 5. Iso-pad Horizontal Excitation

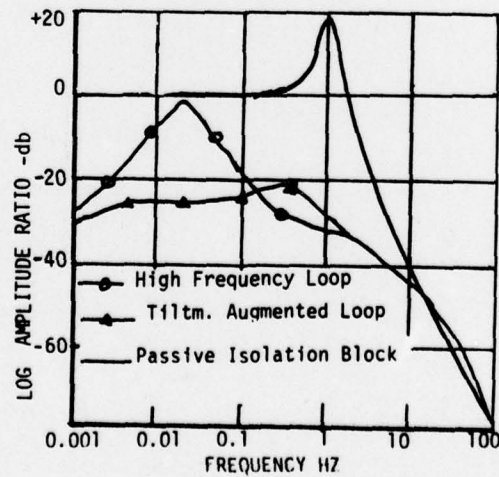


FIGURE 6. Closed Loop Response of High Frequency Angular Control Loop and Tiltmeter Augmented Loop

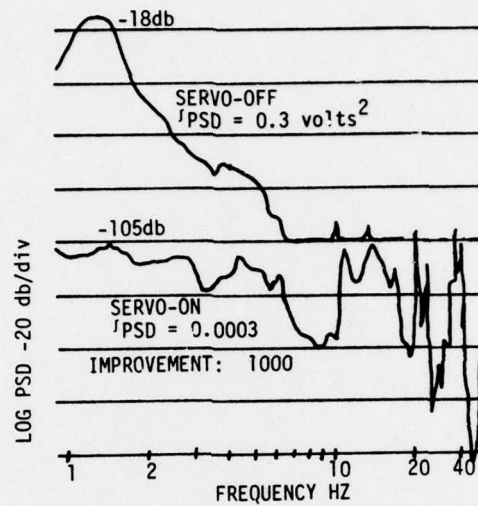


Figure 7. Stability Improvement by N-S Angular Servo

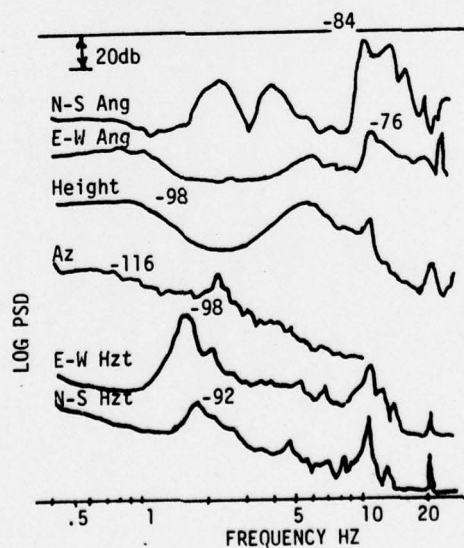


FIGURE 8. Active-servo Performance

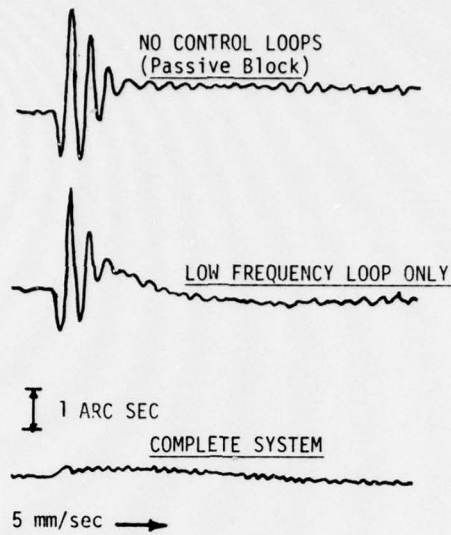


FIGURE 9. Response of the N-S Axis Angular Control System to a 60 lb-ft Step Torque Input

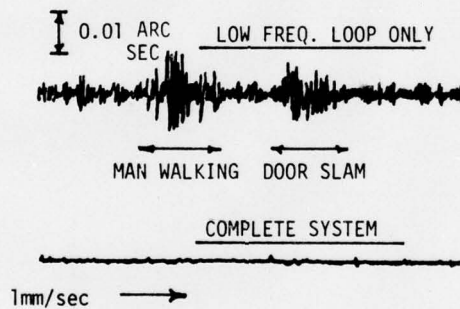


FIGURE 10. Response of the N-S Axis Angular Control System to Ambient Disturbances

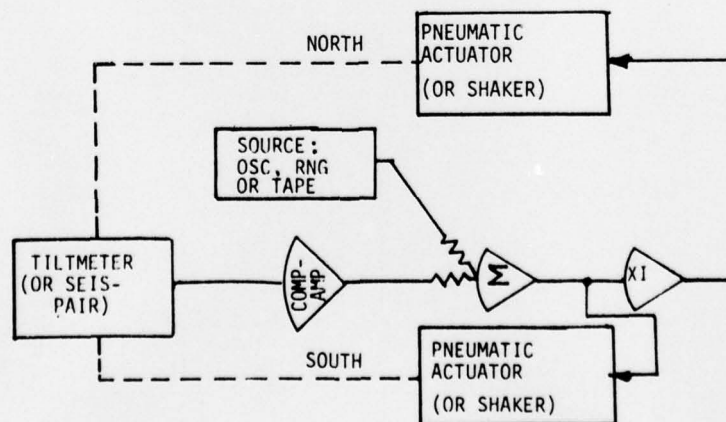


FIGURE 11. Excitation Schematic (Typical)



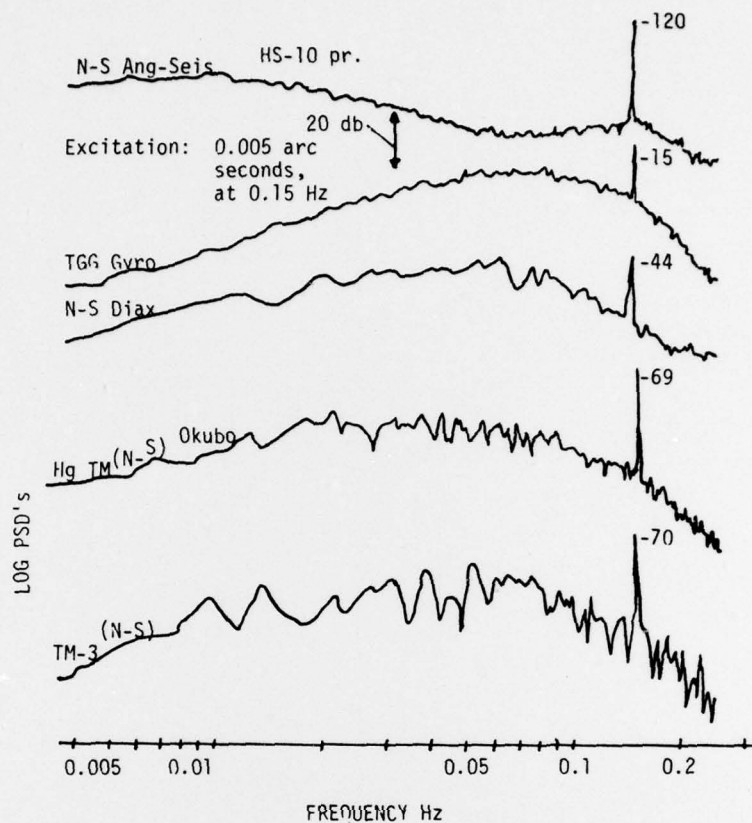


FIGURE 12. Sensors output to 0.005 arc second excitation

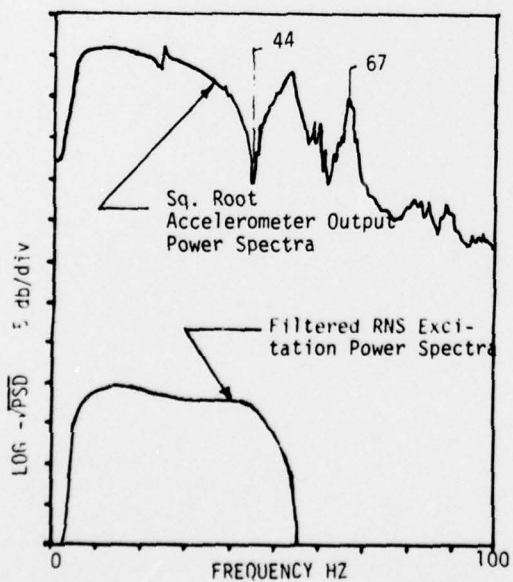


FIGURE 13. High Frequency E-W Angular Excitation

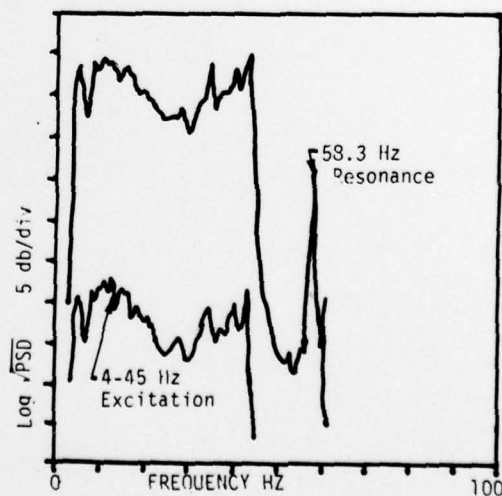


FIGURE 14. High Frequency Vertical Excitation

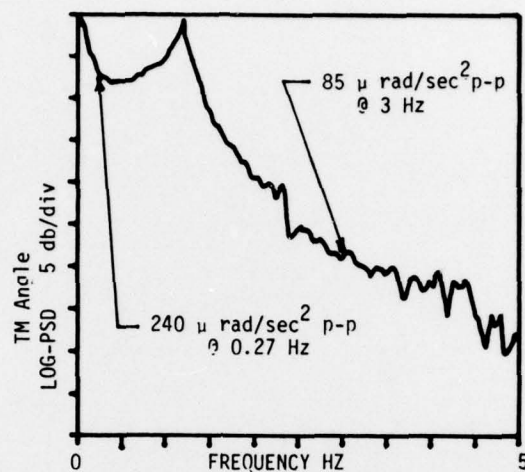


FIGURE 15. Low Frequency Tilt Excitation

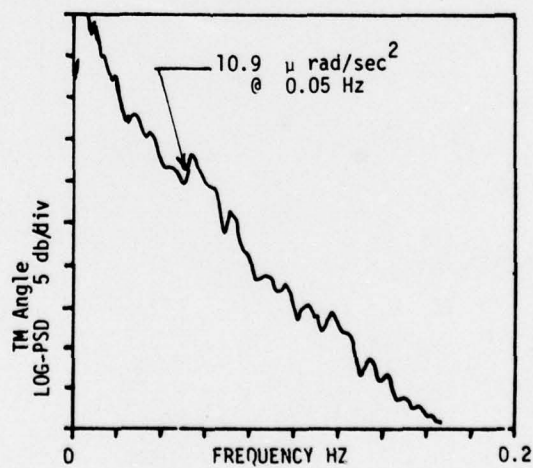


FIGURE 16. Near DC Tilt Excitation